NASA IN-SITU RESOURCE UTILIZATION PROJECT—AND SEAL CHALLENGES

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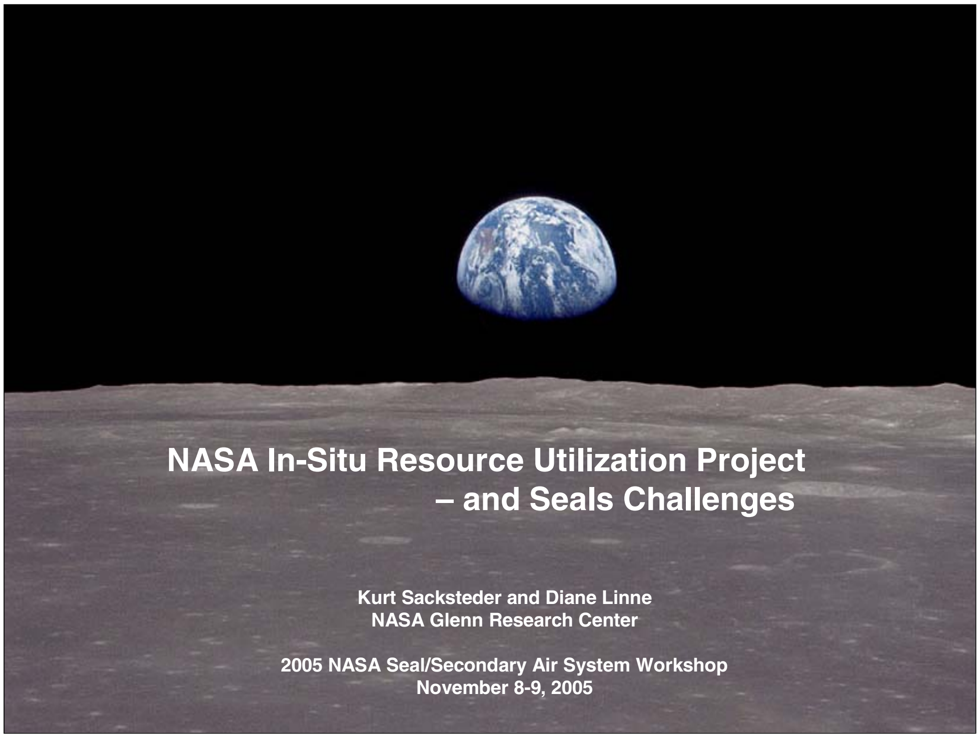
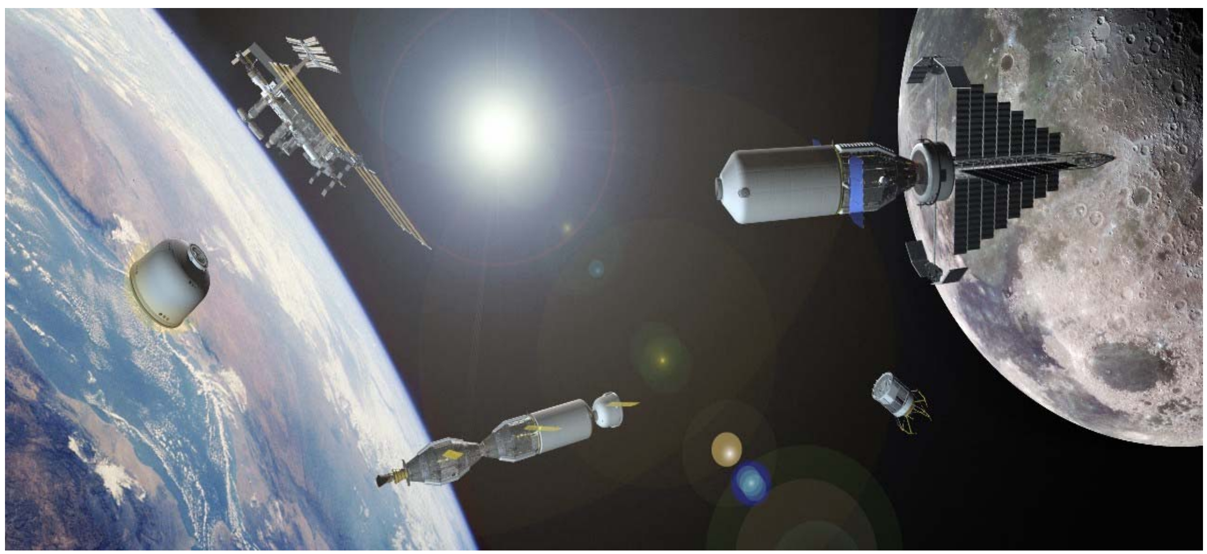


New Space Exploration Vision

- **On January 14, 2004, the President announced a new vision for NASA**
  - Implement a *sustained and affordable* human and robotic program to explore the solar system and beyond;
  - Extend *human presence* across the solar system, starting with a human return to the Moon in preparation for human exploration of Mars and other destinations;
  - Develop the *innovative technologies*, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and
  - Promote *international and commercial participation* in exploration to further U.S. scientific, security, and economic interests.



"Making use of the Moon's abundant resources…"

What Are Space Resources?

- **Traditional material resources including**:
  - Water from the soil or atmosphere
  - Atmospheric gases (CO_2, O_2, N_2, etc.)
  - Volatile species from the solar wind or comets (H_2, He, H_2O, CH_4, etc.)
  - Minerals/metals (Fe, Ti, Ni, Si, etc.)
- **Energy**
  - (Near) Continuous sunlight for electrical/thermal power and stable thermal control
  - (Near) Continuous Darkness for cryogenic fluid storage, scientific instruments and stable thermal control
- **Environment**
  - Vacuum/Dryness
  - Micro/Partial Gravity
  - High Thermal Gradients
- **Location**
  - Stable Locations for Earth/Sun/deep-space observations, mission staging
  - Isolation from Earth's electromagnetic noise, storage of duplicate vital information
  - Isolation for Earth to conduct hazardous testing (nuclear, biological, etc.) and extraterrestrial sample curation & analysis, etc.

In-Situ Resource Utilization exploits these resources, creating products & services that significantly reduce the mass, cost, & risk of extended-duration space exploration

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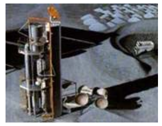
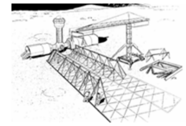
Space Resource Utilization for Exploration





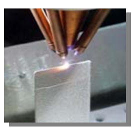

Mission Consumable Production

- **Propellants for Lander/Ascent Vehicles, Surface Hoppers, & Aerial Vehicles**
- **Fuel cell reagents for mobile** (rovers, EVA) & stationary backup power
- **Life support consumables** (oxygen, water, buffer gases)
- Gases for science equipment and drilling
- Bio-support products (soil, fertilizers, etc.)
- Feedstock for in-situ manufacturing & surface construction

Surface Construction

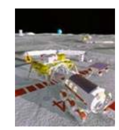
- **Radiation shielding for habitat & nuclear reactors from in-situ resources or products** (Berms, bricks, plates, water, hydrocarbons, etc.)
- **Landing pad clearance**, site preparation, roads, etc.
- Shielding from micro-meteoroid and landing/ascent plume debris
- Habitat and equipment protection




Manufacturing w/ Space Resources

- **Spare parts manufacturing**
- Locally integrated systems & components (especially for increasing resource processing capabilities)
- High-mass, simple items (chairs, tables, replaceable structure panels, wall units, wires, extruded pipes/structural members, etc.)





Space Utilities & Power

- **Storage & distribution of mission consumables**
- Thermal energy storage & use
- **Solar energy** (PV, concentrators, rectennas)
- **Chemical energy** (fuel cells, combustion, catalytic reactors, etc.)

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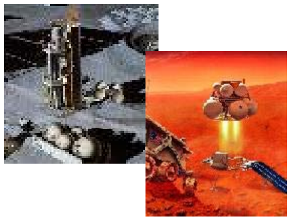
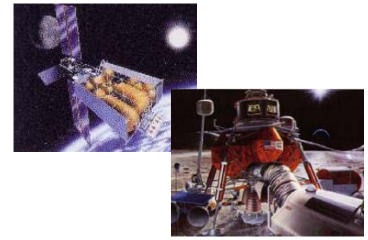
ISRU Enables Affordable, Sustainable & Flexible Exploration



Mass Reduction

Propellant Production
- Reduces Earth to orbit mass by 20 to 45% for Mars missions
- 3.5:1 to 4:1 mass savings leverage from Moon/Mars surface back to Low Earth Orbit

Cost Reduction



- Reduces number and size of Earth launch vehicles
- Allows reuse of transportation assets
- Minimizes DDT&E cost

Space Resource Utilization

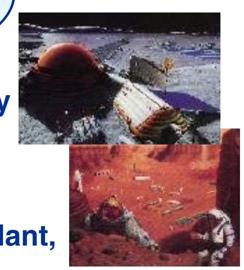
Risk Reduction & Flexibility

- Fewer Earth launches & reduced mission operations
- Reduced dependence on Earth
- Common hardware & mission consumables
- In-situ fabrication of spare parts for sustainable self-sufficiency
- Dissimilar redundancy
- Radiation & Plume Shielding

Enables Space Commercialization

- Material handling and processing technologies
- Infrastructure for space commercialization
- Propellant/consumable depots at Earth-Moon L1 & Lunar Surface

Expands Human Presence



- Increase surface mobility and extend missions
- Habitat & infrastructure construction
- Consumables for propellant, life support, power, etc.
- Substitute infrastructure cargo for Earth-source propellant & consumables

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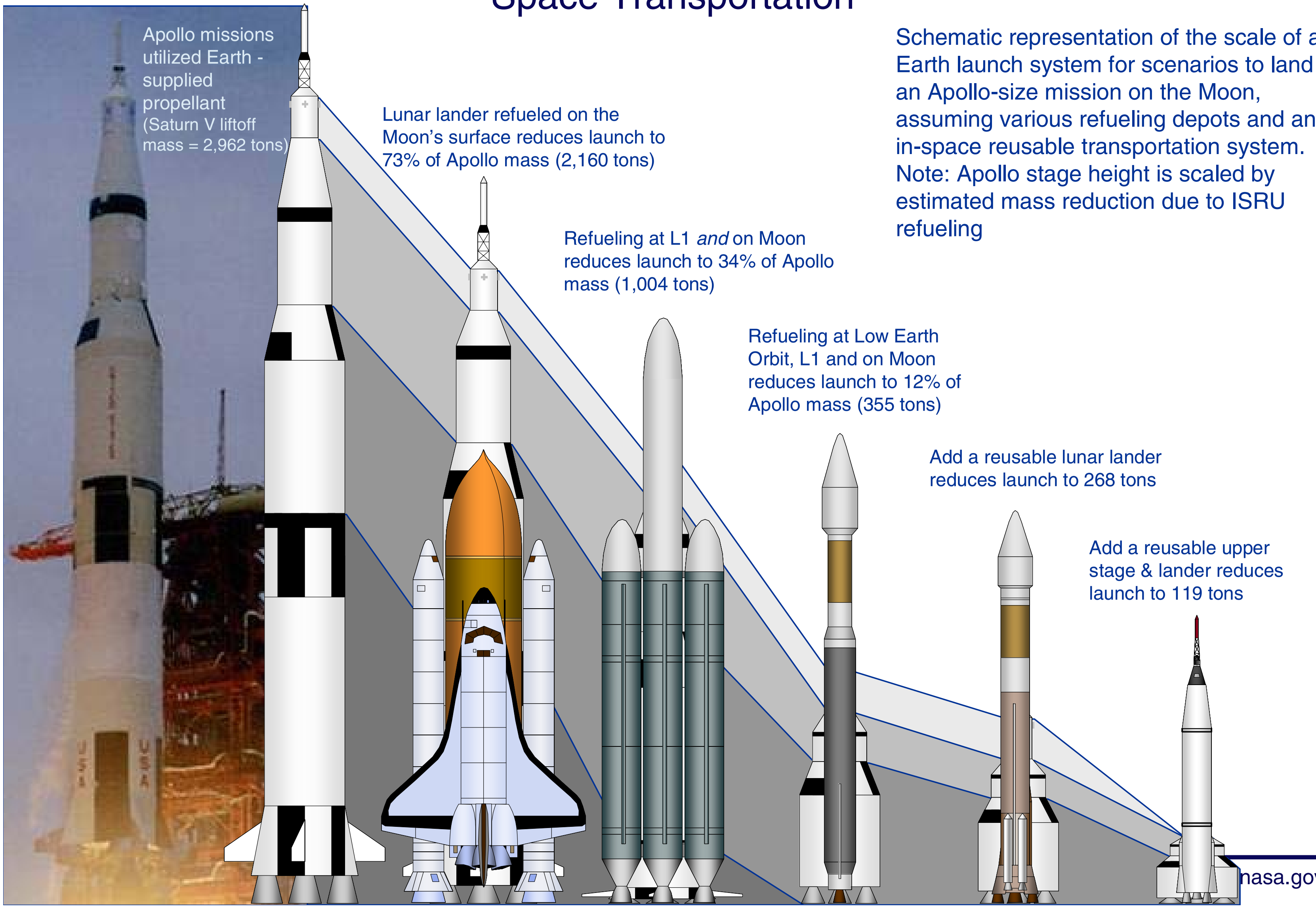
Propellant from the Moon Could Revolutionize Space Transportation

Schematic representation of the scale of an Earth launch system for scenarios to land an Apollo-size mission on the Moon, assuming various refueling depots and an in-space reusable transportation system. Note: Apollo stage height is scaled by estimated mass reduction due to ISRU refueling



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NASA ISRU Capability “Roadmap” Study, 2005

- **In-Situ Resource Utilization 13.0** — Chair: Jerry Sanders/JSC; Co-Chair: Mike Duke (CSM)
  - **Resource Extraction 13.1** — Chair: L. Gertch/UMR & Don Rapp/JPL
    - Resource Assessment 13.1.1
    - Resource Acquisition 13.1.2
    - Resource Beneficiation 13.1.3
    - Site Management 13.1.4
  - **Material Handling & Transportation 13.2** — Chairs: Kurt Sacksteder/GRC & Dale Boucher/NORCAT
    - Fixed Site Transportation 13.2.1
    - Mobile Material Transportation 13.2.2
    - Payload Material Handling 13.2.3
    - Cross Platform Capabilities, Reliability and Logistics 13.2.4
  - **Resource Processing 13.3** — Chairs: Bill Larson/KSC & Larry Clark/LMCO
    - Mission Consumable Production (Life Support & Propellant 13.3.1
    - Feedstock Production for In-Situ Manufacturing 13.3.2
    - Feedstock Production for Surface Construction 13.3.3
    - Common Critical Components 13.3.4
  - **Surface Manufacturing with In-Situ Resources 13.4** — Chair: Peter Curreri/MSFC & Ed McCullough/Boeing
    - Additive Manufacturing Techniques 13.4.1
    - Subtractive Manufacturing Technologies 13.4.2
    - Formative Manufacturing Technologies 13.4.3
    - Locally Integrated Energy Systems 13.4.4
    - Locally Integrated Systems & Components 13.4.5
    - Manufacturing Support Systems 13.4.6
  - **Surface Construction 13.5** — Chair: Kris Romig/JSC & Eric Rice/Orbitec
    - Site Planning 1.5.1
    - Surface & Subsurface Preparation 1.5.2
    - Structure/Habitat Fabrication 1.5.3
    - Radiation & Micro Meteoroid Debris Shielding 1.5.4
    - Structure & Site Maintenance 1.5.5
    - Landing & Launch Site 1.5.6
  - **Surface ISRU Product & Consumable Storage and Distribution 13.6** — Chair: Robert Johnson/KSC & Robert Zubrin/Pioneer Ast.
    - Surface Cryogenic Fluid & Propellant Storage & Distribution 13.6.1
    - Chemical Reagent Storage & Distribution 13.6.2
    - Gas Storage & Distribution 13.6.3
    - Water & Earth Storable Fluid Storage & Distribution 13.6.4
    - Utility Connections & Interfaces 13.6.5
    - Hazard Detection & Suppression 13.6.6
  - **ISRU Unique Development & Certification Capabilities 13.7** — Chair: Diane Linne/GRC & Mike Downey/JSC
    - Modeling & Standards 13.7.1
    - Simulants 13.7.2
    - Unique Test Environments (1-g) 13.7.3
    - Reduced Gravity Test Environments 13.7.4

A Catalog and Timeline of Capabilities for the Utilization of Space Resources

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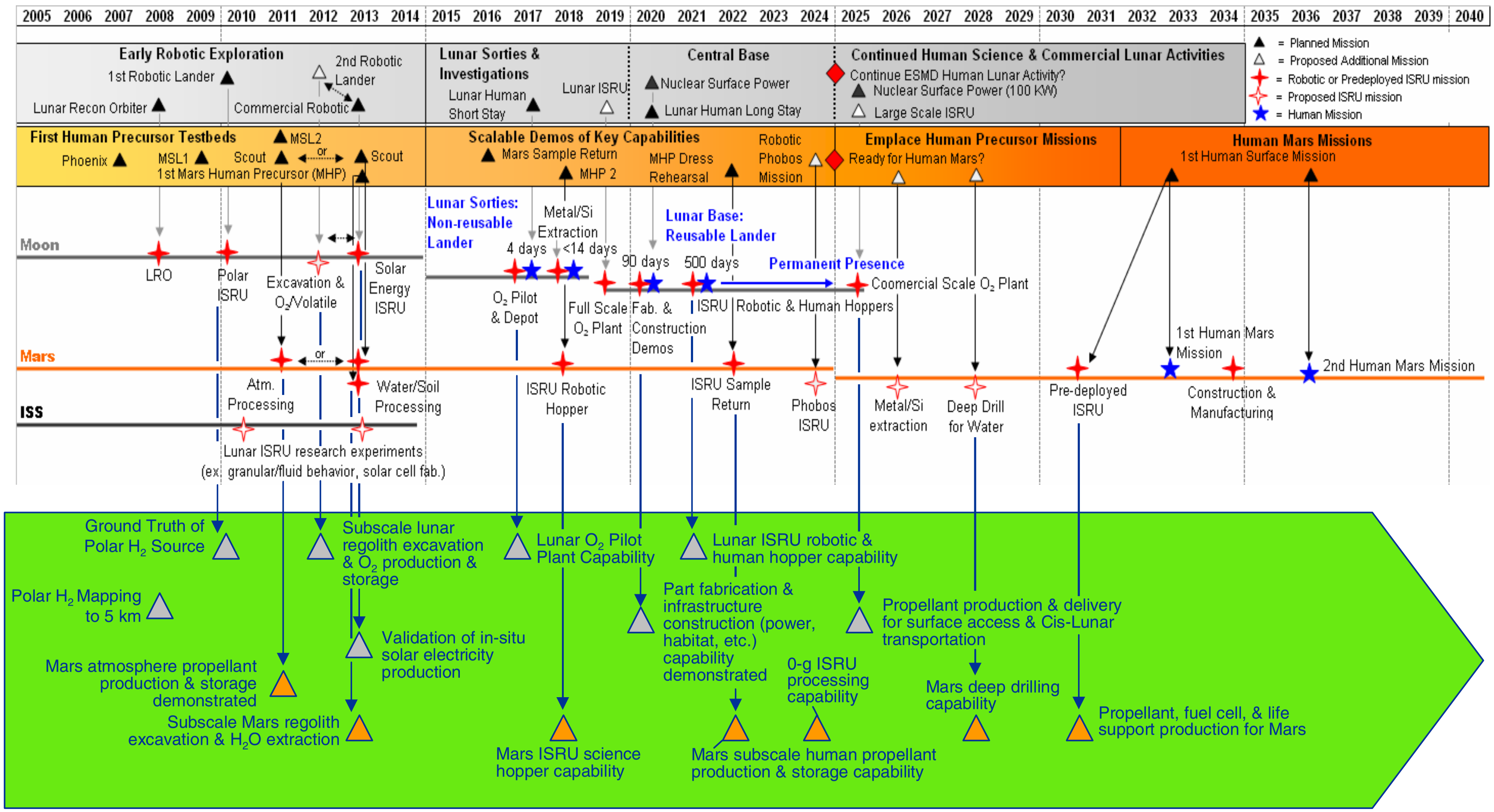
Timeline for ISRU Capability Implementation



In-Situ Resource Utilization must earn acceptance for mission critical roles in crewed missions through convincing demonstrations early in the Exploration timeline

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Lunar ISRU Implementation Approach

Lunar Mission Assumptions with ISRU (Lunar Exploration Analysis Group-LEAG)

- Robotic precursors identify resources and validate critical processes
- Early human missions (4 to 14 days) gain system & operational experience until a candidate long-term site is selected
  - Pre-deployed ISRU/mission assets before human missions
- Develop infrastructure at one base for Mars mission 'dress rehearsals' (90 day & 500 day) and sustained human presence in space
  - Traverse or hop to other locations for short term science mission objectives

Initial Capabilities

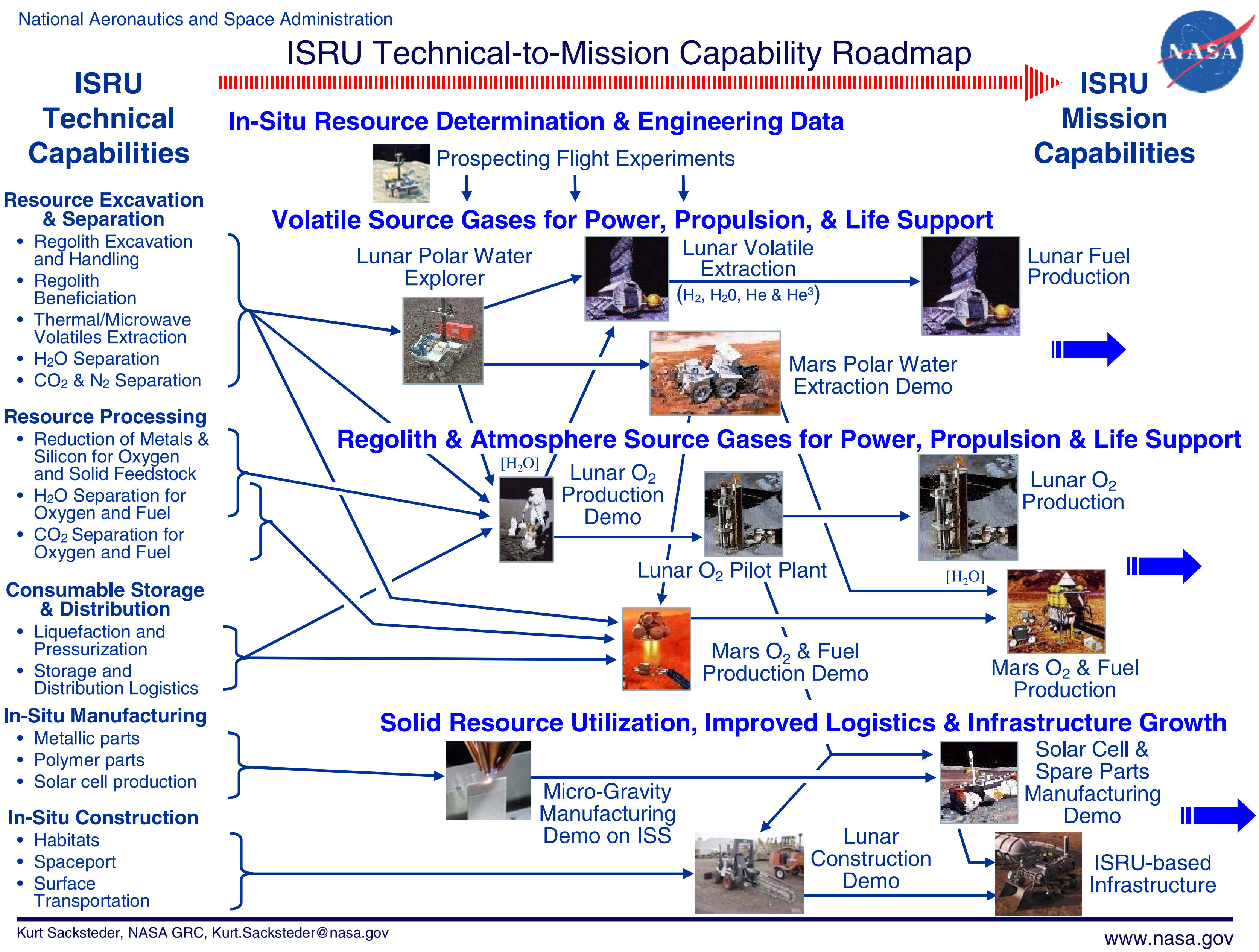
- Surface regolith excavation and manipulation
  - Excavation for volatile extraction and regolith processing
  - Berms and shielding for radiation and plume protection
  - Site/landing pad preparation and road/dust mitigation
- Extraction & recovery of useful volatiles from surface resources (H_2, CO, N_2, H_2O)
- Oxygen (O_2) production from regolith processing
- Production/regeneration of fuel cell reagents
- Cryogenic storage & transfer

Mid-Term ISRU Capabilities

- In-situ fabrication and repair
- Space Power
- Thermal energy storage & use

Long-Term Lunar Capabilities

- In-situ manufacturing of complex parts and equipment
- Habitat and infrastructure construction (surface & subsurface)
- Life Support System – bio support (soil, fertilizers, etc.)
- Helium-3 isotope (^3He) mining



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ISRU Technical-to-Mission Capability Roadmap
ISRU Technical Capabilities
ISRU Mission Capabilities
Resource Excavation & Separation
• Regolith Excavation and Handling
• Regolith Beneficiation
• Thermal/Microwave Volatiles Extraction
• H_2O Separation
• CO_2 & N_2 Separation
Resource Processing
• Reduction of Metals & Silicon for Oxygen and Solid Feedstock
• H_2O Separation for Oxygen and Fuel
• CO_2 Separation for Oxygen and Fuel
Consumable Storage & Distribution
• Liquefaction and Pressurization
• Storage and Distribution Logistics
In-Situ Manufacturing
• Metallic parts
• Polymer parts
• Solar cell production
In-Situ Construction
• Habitats
• Spaceport
• Surface Transportation
In-Situ Resource Determination & Engineering Data
Prospecting Flight Experiments
Volatile Source Gases for Power, Propulsion, & Life Support
Lunar Polar Water Explorer
Lunar Volatile Extraction
(H_2, H_20, He & He^3)
Lunar Fuel Production
Mars Polar Water Extraction Demo
Regolith & Atmosphere Source Gases for Power, Propulsion & Life Support
[H_2O]
Lunar O_2 Production Demo
Lunar O_2 Production
Lunar O_2 Pilot Plant
[H_2O]
Mars O_2 & Fuel Production Demo
Mars O_2 & Fuel Production
Solid Resource Utilization, Improved Logistics & Infrastructure Growth
Micro-Gravity Manufacturing Demo on ISS
Solar Cell & Spare Parts Manufacturing Demo
Lunar Construction Demo
ISRU-based Infrastructure
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ISRU Resources & Products of Interest

LUNAR RESOURCES

MARE REGOLITH

Ilmenite - 15%

$FeO \bullet TiO_2$	98.5%

Pyroxene - 50%

$CaO \bullet SiO_2$	36.7%
$MgO \bullet SiO_2$	29.2%
$FeO \bullet SiO_2$	17.6%
$Al_2O_3 \bullet SiO_2$	9.6%
$TiO_2 \bullet SiO_2$	6.9%

Olivine - 15%

$2MgO \bullet SiO_2$	56.6%
$2FeO \bullet SiO_2$	42.7%

Anorthite - 20%

$CaO \bullet Al_2O_3 \bullet SiO_2$	97.7%

VOLATILES (Solar Wind & Polar Ice/H_2)

Hydrogen (H_2)	50 - 150 ppm
Helium (He)	3 - 50 ppm
Helium-3 (^3He)	10^{-2} ppm
Carbon (C)	100 - 150 ppm
Polar Water (H_2O)/H_2	1 - 10%

→ Thermal Volatile Extraction

Hydrogen Reduction of Ilmenite/glass

Fluidized Bed Reactor

$$2FeTiO_3 + 2H_2 \xrightarrow{900°C} 2H_2O + 2Fe + 2TiO_2 \rightarrow 2Fe$$

Water electrolysis

$$O_2 + 2H_2 \xleftarrow{25°C} 2H_2O \rightarrow O_2$$

Sulfuric Acid Reduction

Desolve/Digest Reactor

$$2FeTiO_3 + 2H_2SO_4 \longrightarrow 2H_2O + 2FeSO_4 + 2TiO_2$$

Electrolysis bed

$$O_2 + 2Fe + 2H_2SO_4 \longleftarrow 2H_2O + 2FeSO_4 \rightarrow O_2, 2Fe$$

Methane Reduction (Carbothermal)

Methane Reduction Furnace

$$2FeTiO_3,\ Fe_2SiO_4,\ FeSiO_3,\ Mg_2SiO_4,\ MgSiO,\ CaSiO_3 + 2CH_4 \xrightarrow{1625°C} 2CO + 4H_2 + 2TiO_2 + 2Fe,\ 2FeO + Si,\ FeO + Si,\ 2MgO + Si,\ MgO + Si,\ CaO + Si \rightarrow 2Fe,\ Si$$

Methane Reformer

$$2H_2O + 2CH_4 \xleftarrow{250°C} 2CO + 6H_2$$

Water electrolysis

$$2H_2O \xrightarrow{25°C} 2H_2 + O_2 \rightarrow O_2$$

Molten Electrolysis

Molten Electrolysis Reactor

$$2SiO_2 \rightarrow 2SiO + O_2 \rightarrow O_2$$
$$2FeTiO_3 \rightarrow 2Fe + 2TiO_2 + O_2 \rightarrow O_2, 2Fe$$
$$2FeO \rightarrow 2Fe + O_2$$

Vapor Pyrolysis

Pyrolysis Reactor/Condenser

$$2SiO_2 \xrightarrow{>2000°C} 2SiO + O_2 \rightarrow O_2$$
$$2FeTiO_3 \xrightarrow{2500°C} 2Fe + 2TiO_2 + O_2 \rightarrow O_2, 2Fe$$
$$2FeO \xrightarrow{>2000°C} 2Fe + O_2$$
$$2Al_2O_3 \xrightarrow{>2000°C} 4AlO + O_2 \rightarrow O_2$$
$$2Al_2O_3 \xrightarrow{>2000°C} 2AlO + 2Al + O_2 \rightarrow O_2, 2Al$$
$$2MgO \xrightarrow{>2000°C} 2Mg + O_2 \rightarrow O_2$$
$$2CaO \xrightarrow{>2000°C} 2Ca + O_2$$
$$2CaAl_2Si_2O_8 \xrightarrow{2500°C} 2Ca + 4AlO + 4SiO + 4O_2 \rightarrow 4O_2, 2Ca$$
$$2CaAl_2Si_2O_8 \xrightarrow{2500°C} 2Ca + 2AlO + 2Al + 4SiO + 5O_2 \rightarrow 5O_2, 2Al, 2Ca$$

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Challenging Seals Requirements for ISRU

The Moon is a Harsh Environment

- Temperatures from 40K (-230C) to 450K (150C)
- High Vacuum, 10^{-10} mm Hg
- Dust: abrasive, static cling, etc.
- Partial gravity

Initial ISRU Capabilities

- Surface regolith excavation and manipulation – mechanism bearings and regolith abrasion
  - Excavation for volatile extraction and regolith processing
  - Berms and shielding for radiation and plume protection
  - Site/landing pad preparation and road/dust mitigation
- Extraction & recovery of useful volatiles from surface resources (H_2, CO, N_2, H_2O) – encapsulate regolith during excavation and heating
- Oxygen (O_2) production from regolith processing – high temperature reactors and reagent recovery systems
- Production/regeneration of fuel cell reagents – fuel transfer operations
- Cryogenic storage & transfer – valves and other plumbing issues